

# The DSN VLBI System Mark IV-85

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*The DSN VLBI System was established as a Network system in 1978. This article describes the evolution of the VLBI System from Mark I-79 to Mark IV-85 and discusses the system functional requirements for Mark IV-85.*

## I. Introduction

Very long baseline interferometry (VLBI) is a capability implemented in the Network to support flight project navigation requirements and provide station frequency standard stability measurements to validate the hydrogen maser frequency standard performance.

To manage this new major implementation, a DSN VLBI Program was established and led by a program manager from the TDA Office and a task manager from the implementing divisions. The initial functional requirements were reviewed in February 1978. The phases of implementation are described in Ref. 1.

This article updates the functional description and requirements given in Ref. 1 and defines the levels of implementation that constitute the Mark I-79, Mark II-81, Mark III-83, and Mark IV-85 VLBI Systems.

## II. Definition

Very long baseline interferometry is a method of measuring the time of arrival of a radio signal at two locations very distant from each other on the Earth's surface. From the measurement of difference in time of arrival, the position of the

radio source and/or several other parameters of the problem can be determined. These other parameters include Universal Time One (UT1) (the instantaneous rotational angle of the Earth), polar motion, the relative position of the two stations, and the time offset and rate of change of the clocks at the two stations.

The levels of implementation are defined as Mark I-79, Mark II-81, Mark III-83, and Mark IV-85 VLBI Systems.

The Mark I-79 VLBI System, implemented in 1979, provides time offset, rate of change of the clocks at the two stations, Universal Time One (UT1), and polar motion to the following performance:

Time offset: < 20 nanoseconds

Clock rate of change: < 3 parts in  $10^{13}$

Universal Time One: < 1.25 milliseconds

Polar motion: < 50 centimeters

The Mark II-81 VLBI System adds delta differential one-way range ( $\Delta$ DOR) capability for use by flight projects' navigation in determining the angle between the spacecraft and a reference extragalactic radio source (EGRS). The differential

time delay between the spacecraft and EGRS is measured by the DSN to  $< 30$  centimeters.

The Mark III-83 VLBI System improves the accuracy and operability of the Mark I-79 and Mark II-81. The accuracies available are:

Time offset:  $< 10$  nanoseconds

Clock rate of change:  $< 7$  parts in  $10^{14}$

Universal Time One:  $< 0.75$  milliseconds

Polar motion:  $< 30$  centimeters

All equipment used for determining the above parameters are operational and calibration data for troposphere, ionosphere, and the VLBI instrument are available. Improved hydrogen masers with a stability of  $\approx 7$  parts in  $10^{15}$  will be implemented for fully operational capability.

The Mark IV-85 VLBI System adds the wide channel bandwidth (WCB) for operational support of radio source catalog update and maintenance and two-station baseline measurements. The accuracies are as follows:

Absolute radio source location:  $< 5$  microradians

Relative radio source location:  $< 50$  nanoradians

Two station baseline:  $< 3$  centimeters

### III. Mark IV-85 VLBI System Description

#### A. Introduction

The Narrow Channel Bandwidth (NCB) and Wide Channel Bandwidth (WCB) VLBI System will be implemented at the 64-meter antenna and the 34-meter listen-only (X-Y mount) antenna. Data acquisition, formatting, and recording are performed by the common equipment in the Signal Processing Center (SPC). A simplified block diagram indicating switching capability of the 64-meter and 34-meter antennas is shown in Fig. 1. The NCB VLBI System data are recorded at each DSS and transmitted via GCF wideband data lines at the GCF line rate. Ancillary data such as angles, angle residuals, weather data, predicts, and control data are routed via GCF wideband data lines to the Network Operations Control Center (NOCC) VLBI Processor Subsystem (VPS) where they are used to control and calibrate the VLBI data being correlated. The correlated output is used to compute: (1) time and time-rate offset, (2) polar motion and Universal Time, and (3) delta differential one-way range for spacecraft navigation.

The WCB VLBI System records data at 4 to 112 megabits/second rates (in the Haystack Observatory Mark III compatible format) for wideband correlator processing. WCB VLBI data tapes generated at the DSS are mailed to the JPL/CIT correlator for processing. The ancillary data are the same for both the NCB and WCB systems.

VLBI predictions are generated by the Predict Program in the NOCC Support Subsystem and transmitted to each DSS for antenna pointing and frequency control. Control messages of DSS assemblies used for VLBI are generated by the NOCC Support Subsystem and transmitted to the DSS Monitor and Control Subsystem. Monitor of DSS assemblies used for VLBI data acquisition is performed by the assemblies and collected by the DSS Link Monitor and Control Subsystem. These data are forwarded to NOCC via high-speed data lines (HSDL) for display and analysis of the DSN VLBI System.

Both NCB and a sample of WCB VLBI are correlated in near-real time by the NOCC correlator. Validation of the correlation results are displayed for the analysts for the Network Operations Control Team (NOCT) and are transmitted to the DSS for display and analysis.

#### B. Key Characteristics

The key characteristics of the NCB and WCB VLBI systems are given in Table 1.

#### C. Functions and Interface

1. **Narrow Channel Bandwidth (NCB) VLBI.** To determine intercomplex time and time-rate offsets, and universal time and polar motion, narrow band VLBI acquisition of at least 10 radio sources at S- and X-band frequencies must be accomplished. For precision measurements, Coherent Comb Generators Assemblies must be used to calibrate the RF downlink. The determination of these parameters utilizes the functions and interfaces as shown in Fig. 2. VLBI data acquisition is obtained by rapidly switching a pair of 64-meter DSS between radio sources.

The NCB VLBI System is also used to acquire differenced time delay data for Delta Differential One-Way Range ( $\Delta$ DOR). In the acquisition of these data, the antenna pairs are rapidly switched between a spacecraft and a nearby natural radio source.

NCB VLBI data are correlated in the NOCC VLBI Processing Subsystem (VPS) to obtain intercomplex time and time rate offset, universal time, polar motion, and data for  $\Delta$ DOR. An accurate radio source catalog is required to measure these parameters.

Interfaces to the NCB VLBI System are natural radio sources, spacecraft signals, predicts, configuration and control data, frequencies, and timing pulses and epoch time.

Interfaces from the NCB VLBI System are time and time rate offset; Universal time and Polar motion, and spacecraft and radio source delay data.

**2. Wide Channel Bandwidth (WCB) VLBI System.** The purpose of WCB VLBI (Fig. 3) is to provide accurate radio source catalog and intercomplex baseline data for station locations. The inputs are X- and S-band signals from natural radio sources, predicts, control, frequencies, timing pulses, and epoch time. Outputs are the updated radio source catalog and intercomplex baselines.

Wide Channel Bandwidth (WCB) VLBI is used as backup to NCB for  $\Delta$ DOR data reliability. It is also used for  $\Delta$ DOR where the natural radio source signal-to-noise ratio is not sufficient for NCB VLBI data acquisition and correlation.

## **IV. System Functional Requirements and Performance**

### **A. General**

This section defines the DSN VLBI System functional requirements to support Project VLBI requirements for spacecraft navigation. It defines the DSN VLBI functional requirements imposed on the DSS, Ground Communications Facility (GCF), and NOCC. Figures 1 and 2 present the DSN VLBI System functions and interface for NCB and WCB VLBI respectively. A block diagram of functions and data flow for the Mark IV-85 VLBI System is shown in Fig. 5.

### **B. Project Requirements**

Project requirements (Table 2) are derived from Project Requirements and DSN Support Plan for the following missions:

- (1) Voyager II
- (2) Galileo
- (3) VOIR

### **C. DSS Functions and Performance Requirements**

This paragraph presents the performance requirements imposed on the DSS by the DSN VLBI System. DSS functions, subsystems and interfaces are given in Fig. 5.

VLBI predictions, system configuration, and data mode messages stored by the DSS Link Monitor and Control Subsystem are used to configure and control the DSS subsystems

for VLBI data acquisition. The DSS Link Monitor and Control is controlled and monitored by the DSS Complex Monitor and Control.

Antenna pointing control of the DSS antenna is given in Table 3. A pointing error matrix is used to provide position offsets to maintain pointing accuracy.

A description of the acquisition of VLBI signals follows.

**1. Narrow Channel Bandwidth (NCB) VLBI.** The frequency span bandwidths are 40 MHz at S-band and 100 MHz at X-band. Therefore, frequency range shall be 2265 to 2305 MHz at S-band and 8400 to 8500 MHz at X-band. Therefore, operating system temperature is  $< 27$  K at S-band and  $< 24$  K at X-band. Polarization shall be right-hand circular polarized (RCP). Phase stability is  $< 14$  deg rms at S-band and  $< 50$  deg rms at X-band.

Up to 12 selectable VLBI downconverted radio frequency channels are provided (four at S-band and eight at X-band). Up to three calibration tones shall be provided for each IF – video converted channel.

**2. Wide Channel Bandwidth (WCB) VLBI.** RF frequency span bandwidth is 100 MHz at S-band and 400 MHz at X-band, which will require user supplied microwave equipment. Frequency range is 2235 to 2335 MHz at S-band and 8100 to 8580 MHz at X-band. System operating temperature shall be  $< 120$  K at S-band and  $< 100$  K at X-band. Phase stability is  $< 14$  deg rms at S-band and  $< 50$  deg rms at X-band.

**3. 40/100 MHz Bandwidth.** Frequency bandwidth is 40 MHz at S-band and 100 MHz at X-band. Frequency range is 2265 to 2305 MHz at S-band and 8400 to 8500 MHz at X-band. System operating temperature is  $< 27$  K at S-band and  $22$  K at X-band. Phase stability is  $< 100$  deg (0.1 to 30 sec) at S- and X-band frequencies.

There are eight RF downconverted channels selectable within the bandwidth of the received frequency bandwidth. Up to three calibration tones are supplied for each frequency channel.

**4. Coherent Comb Generator.** A coherent reference frequency is to be transmitted from the DSS primary frequency reference to the Configuration Control Group (CCG) where coherent tones are generated and inserted into the S- and X-band RF receiving channels. The tones generated by the CCG are used to calibrate the VLBI data acquisition system for phase instabilities in the VLBI instrument. The tones have hydrogen maser stability as specified in Fig. 6.

Sampling and recording of VLBI data channels are now described.

**1. Narrow channel bandwidth.** VLBI data sampling of up to 12 video band channels is provided with time multiplexing of channels. Sampling and recording rates of 500, 250, 125, and 62.5 kilobits/second are provided.

**2. Wide channel bandwidth.** Simultaneous VLBI data sampling of eight video band channels is provided with expansion to 28 video band channels. Sampling and Recording rates of 4, 2, 1, 0.5 and 0.25 megabits/second are provided for each channel. The tape format is compatible with the Haystack Observatory Mark III VLBI data tapes.

Ancillary data are sampled and recorded with the VLBI data. The ancillary data consists of such data as follows:

- (1) VLBI predicts.
- (2) Subsystem configuration, status, and data mode.
- (3) Angles and angle residuals.
- (4) Recorder status.
- (5) Ground weather data.
- (6) Water vapor radiometer data.
- (7) Ionosphere data.
- (8) Other.

Configuration, status performance, and data mode are transferred from the relevant subsystem to the Occultation Data Assembly (ODA) for inclusion with the ancillary data. Monitor data are also be routed to the DSN Maintenance Center (DMC) for DSS operations display together with other ancillary data.

NCB ancillary and VLBI data are transmitted at the maximum wide-band data line (WBDL) rate to the NOCC for validation of two-station VLBI data and for near-real-time VLBI correlation and parameter estimation. WCB data tape of ancillary and VLBI data is mailed to JPL. A portion of WCB VLBI data and ancillary data is transmitted via WBDL for VLBI validation.

Monitor data from ODA is transmitted via HSDL to the Radio Science Real Time Monitor Assembly for evaluation and display to the Network Operations Control Team. This monitor data is the VLBI related subsystem parameters and a subset or all of the ancillary data.

## D. GCF Functional Requirements

The functions, subsystems, and interfaces of the GCF use for VLBI are given in Fig. 7.

The WBDL is used to transmit NCB ancillary and VLBI data from the DSS to the NOCC VLBI Processor Subsystem (VPS) in near-real time. NCB VLBI maximum data acquisition rate is 500 kilobits/second. This amounts to  $5 \times 10^8$  bits or 10,000 seconds of GCF wide band data transmission for each narrow band VLBI observation. WBDL data throughput should be  $> 95\%$  for time offset, and rate and earth platform parameter observations, and  $> 98\%$  of data for  $\Delta$ DOR observations. Selective recall will be available to fill in data outages. Though WBDL is routed directly to the NOCC VLBI Processor Subsystem, a capability of generating IDRs is provided.

The HSDL provides transmission of VLBI predicts, configuration, data mode, and replay requests from the NOCC to the DSS. HSDL throughput shall be  $> 99.8\%$  of these data with no detected errors. End-to-end verification of data sent versus data received is performed by the sending and receiving subsystems. Replay requests are initiated by the receiving subsystem to the transmitting subsystem for retransmission.

The HSDL provides transmission of VLBI monitor and ancillary data and replay requests from the DSS to the NOCC. HSDL throughput will be  $> 98\%$  with no detected errors. Replay requests are issued by the receiving subsystem to the transmitting subsystem for retransmission.

## E. NOCC Functional Requirements

The functions, subsystems, and interfaces of the NOCC used for VLBI are given in Fig. 8.

VLBI predictions are to be generated from a natural radio source catalog that is generated and maintained by the WCB VLBI data system. Spacecraft predictions for  $\Delta$ DOR are computed from a project supplied trajectory tape. The NOCC provides a file of predictions for each observation (assume a maximum of 10 observations).

The NOCC verifies that the DSS system configuration and mode corresponds to that planned for the VLBI observation sessions. Alarms are generated for all mismatches. Displays are made of the system configuration, and data mode alarms. System status and alarms are transmitted to the DSS Monitor and Control System. Also the VPS shall correlate VLBI data from two stations to determine quality. Reports of VLBI quality are supplied to NOCC displays and transmitted to DSS Monitor and Control System for DSS operations display.

The following parameters are determined from NCB VLBI data:

Mark I-79:

- (1) Interstation time offset and rate  $< 20$  nanoseconds and  $< 1 \times 10^{-13}$ , respectively.
- (2) Universal time and polar motion  $< 1.25$  milliseconds and  $< 50$  centimeters, respectively.
- (3) Differential spacecraft and quasar time delay  $< 30$  centimeters.

Mark III-83:

- (1) Interstation time offset and rate  $< 10$  nanoseconds and 7 parts in  $10^{14}$ , respectively.
- (2) Universal Time One and polar motion  $< 0.75$  millisecond and 30 centimeters, respectively.
- (3) Differential spacecraft and quasar time delay  $< 10$  centimeters.

VLBI Processing Subsystem performs the following NCB functions:

- (1) The VLBI and ancillary data are received via WBDL or from a VLBI IDR. An accountability record is made and automatic replay request messages generated to provide the required data.

The ancillary data is used with the accountability data to edit the VLBI data for cross correlation.

- (2) The NOCC VPS will be a twelve-channel, two-station, one-baseline processor dedicated to DSN applications. During NCB VLBI observations, the twelve bandwidth-synthesis channels will be time multiplexed.
- (3) The correlation rate is selected to ensure that the correlation process can handle the data acquisition without backlog. It is highly desirable to have the correlation process run equal to or faster than WBDL rates.
- (4) To calibrate the VLBI data, a known signal of constant frequency is injected at the receiver during a VLBI observation. During correlation, the Correlator Assembly will generate (with a local model) this same frequency and calibrate for phase changes due to drifts in the microwave and receiver.
- (5) The correlation software generates the geometric delay and phase and sends the data to the hardware correlator. Due to quantization and round-off, the hardware may not exactly track the software. However, the error shall be less than  $10^{-4}$  cycles of fringe.

- (6) Given a set of parameters, the software model shall calculate the phase to within  $10^{-5}$  cycles of fringe. Also, a record of the calculations along with their results will be kept with a precision of  $10^{-5}$  cycles of fringe.
- (7) The software model constantly updates its computation of the required geometric delay lag due to the earth's rotation. Eight instantaneous lags (four preceding and four following the nominal geometric delay) shall be provided to determine the actual geometric delay. The maximum equivalent error of the VPS in tracking the model delay (the error in keeping constant the point of maximum correlation) shall be 0.01 lag.
- (8) The postcorrelation functional requirements for delta DOR are as follows:
  - (a) Receive spacecraft predicts tape from project navigation.
  - (b) Compute quasar and spacecraft phase.
  - (c) Compute VLBI time delay for the quasar and spacecraft.
  - (d) Provide quasar and spacecraft delay tape to project navigation.
- (9) The postcorrelation functional requirements for time and time rate, UTI, and polar motion are as follows:
  - (a) Compute quasar and tone phase.
  - (b) Calibrate quasar phase for station instrument errors.
  - (c) Compute calibrated quasar delay.
  - (d) Resolve cycle ambiguities.
  - (e) Compute preliminary clock parameters.
  - (f) Calibrate for transmission media effects.
  - (g) Solve for time and time rate, UTI, and polar motion.
  - (h) Provide solved-for parameters to project navigation after validation.

Functional requirements for the WCB VLBI processor subsystem are given below:

- (1) The WCB VLBI Processor must be capable of simultaneously correlating VLBI data from three stations, with expansion to seven stations. It must also be able to correlate, in parallel, 28 frequency channels per station.

- (2) To calibrate the VLBI data, known time signals of constant frequency shall be injected in the microwave subsystem during a VLBI observation. During correlation, the Correlator Assembly will generate (with a local model) this same frequency and measure its phase change due to phase instabilities in the microwave and receiver subsystems.
- (3) The correlation software generates the geometric time delay and phase and sends the data to the hardware correlator. Due to quantization and round-off, the hardware may not exactly track the software. However, the error shall be less than  $10^{-4}$  cycles of fringe.
- (4) Given a set of parameters, the software model shall calculate the phase to within  $10^{-5}$  cycles of fringe. Also, a record of the calculations along with their results will be kept with a precision of  $10^{-5}$  cycles of fringe. Output should be available in both delay and frequency domain.
- (5) The software model constantly updates its computation of the required geometric delay lag due to the earth's rotation. Eight instantaneous lags (four preceding and four following the nominal geometric delay) shall be provided to determine the actual geometric delay. The maximum equivalent error of the JPL/CIT VLBI Processor tracking the model delay (the error in keeping constant the point of maximum correlation) shall be 0.01 lag.
- (6) The JPL/CIT VLBI Processor subsystem shall be able to process data collected and recorded by GSFC/Haystack Mark III VLBI System.
- (7) Postcorrelation functional requirements are as follows:
  - (a) Compute quasar and tone phase.
  - (b) Calibrate quasar phase for station instrument error.
  - (c) Compute calibrated quasar delay.
  - (d) Resolve cycle ambiguities.
  - (e) Calibrate for transmission media effects.
  - (f) Solve for quasar locations and baseline.
  - (g) Update radio source catalog and baselines.

## Reference

1. Chaney, W. D., and Ham, N. C., "DSN VLBI System Mark I-80," in *The Deep Space Network Progress Report 42-56, January and February 1980*. Jet Propulsion Laboratory, Pasadena, Calif., April 15, 1980.

**Table 1. VLBI system key characteristics**

Narrow Channel Bandwidth (NCB)
Near-real-time interstation time and frequency measurements
Universal time and polar motion determination
Delta differential one-way range
NCB VLBI capability at one 64-meter and one 34-meter antenna, each complex (with shared SPC equipment)
Centralized monitor and control of system by NOCC
Data rates of 62.5, 125, 250 and 500 kbits/second
On-site recording of NCB signals with near-real-time playback through GCF at prevailing GCF wideband rates
Correlation and postcorrelation processing performed in NOCC
Near-real-time "quick-look" processing for system validation
VLBI validation feedback from VPS to DSS
Moderate RF span bandwidths
Wide Channel Bandwidth (WCB) VLBI
Radio source catalog maintenance
Intercomplex distance determination
WCB VLBI capability at one 64-meter and one 34-meter antenna, each complex (with shared SPC equipment)
Centralized monitor and control of system by NOCC
Data rate up to 112 megabits/second (compatible with Haystack Mark III VLBI data acquisition system)
On-site recording of wide-band signals on tape. Tape shipped to correlation processing facility
Correlation and postcorrelation processing performed at Caltech
Near-real-time "quick-look" processing using the NOCC VPS
VLBI validation feedback from VPS to DSS
Moderate and wide RF span bandwidth

**Table 2. VLBI System functional project requirements**

Voyager
Calibration of Intercomplex time rate to $3 \times 10^{-13}$ ( $1 \times 10^{-13}$ desired)
Calibration of UT-1 and polar motion to < 50 centimeters (desired)
Use of differential time delay for $\Delta$ DOR to validate two-station ranging (Voyager II demonstration)
$\Delta$ DOR for Voyager II Saturn-to-Uranus navigation (accuracy equivalent to two-station differenced range)
Galileo
Differential time delay for $\Delta$ DOR to < 30 centimeters
Calibration of intercomplex time rate to $3 \times 10^{-13}$ ( $1 \times 10^{-13}$ desired)
Calibration of universal time and polar motion to < 50 centimeters (desired)
Voir
Narrowband $\Delta$ DOR to 10 centimeters

**Table 3. Antenna pointing control**

Parameter	64-meter DSS	34-meter DSS
Pointing accuracy	0.002 deg	0.005 deg
Tracking rate (HA/dec)	0 to 0.004 deg/s	0 to 0.004 deg/s
Maximum slew rate (HA/Dec)	0.25 deg/s	0.70 deg/s
Visibility: elevation	7 to 90 deg	7 to 90 deg
azimuth	$\pm 180$ deg	$\pm 180$ deg

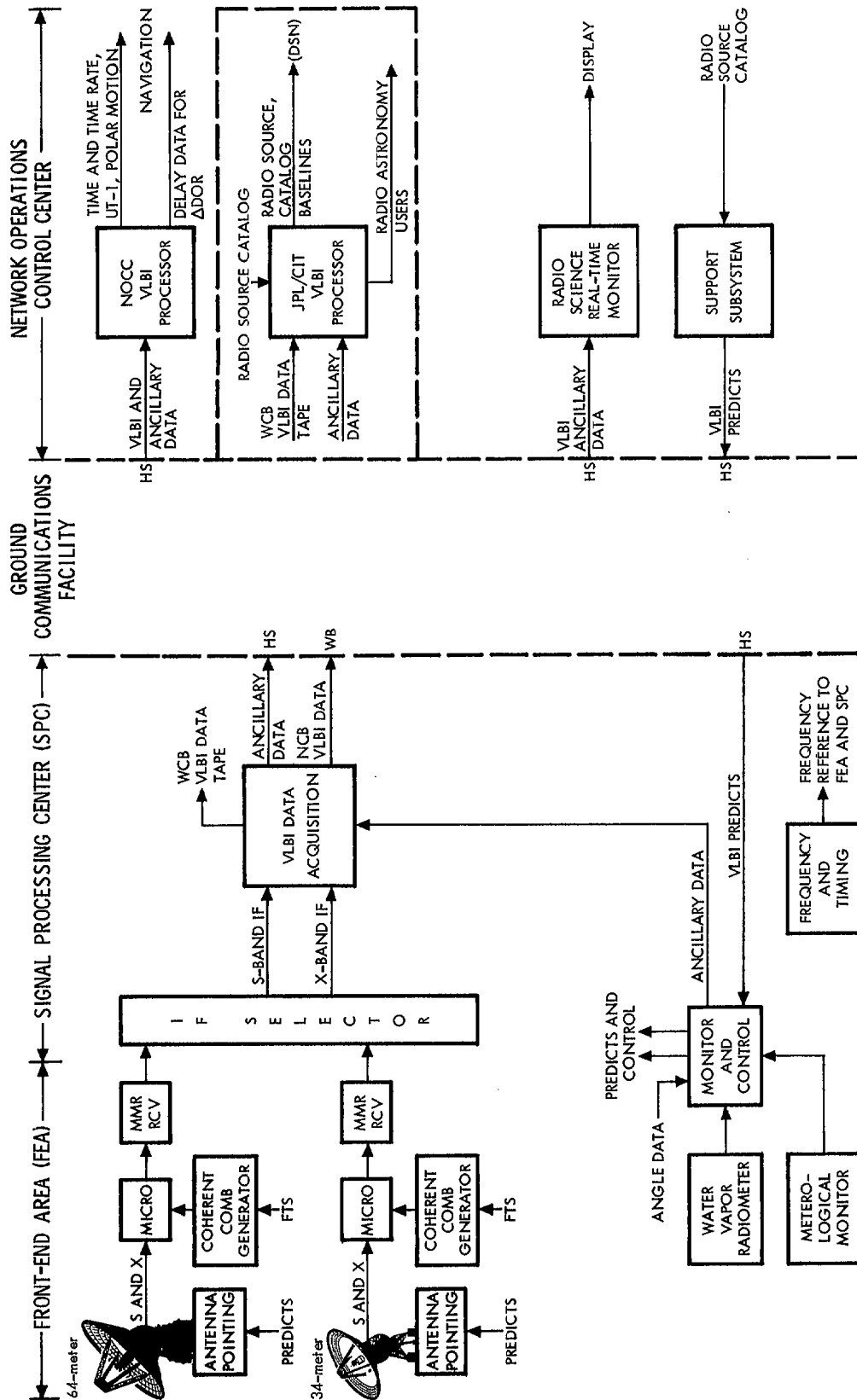


Fig. 1. VLBI System block diagram

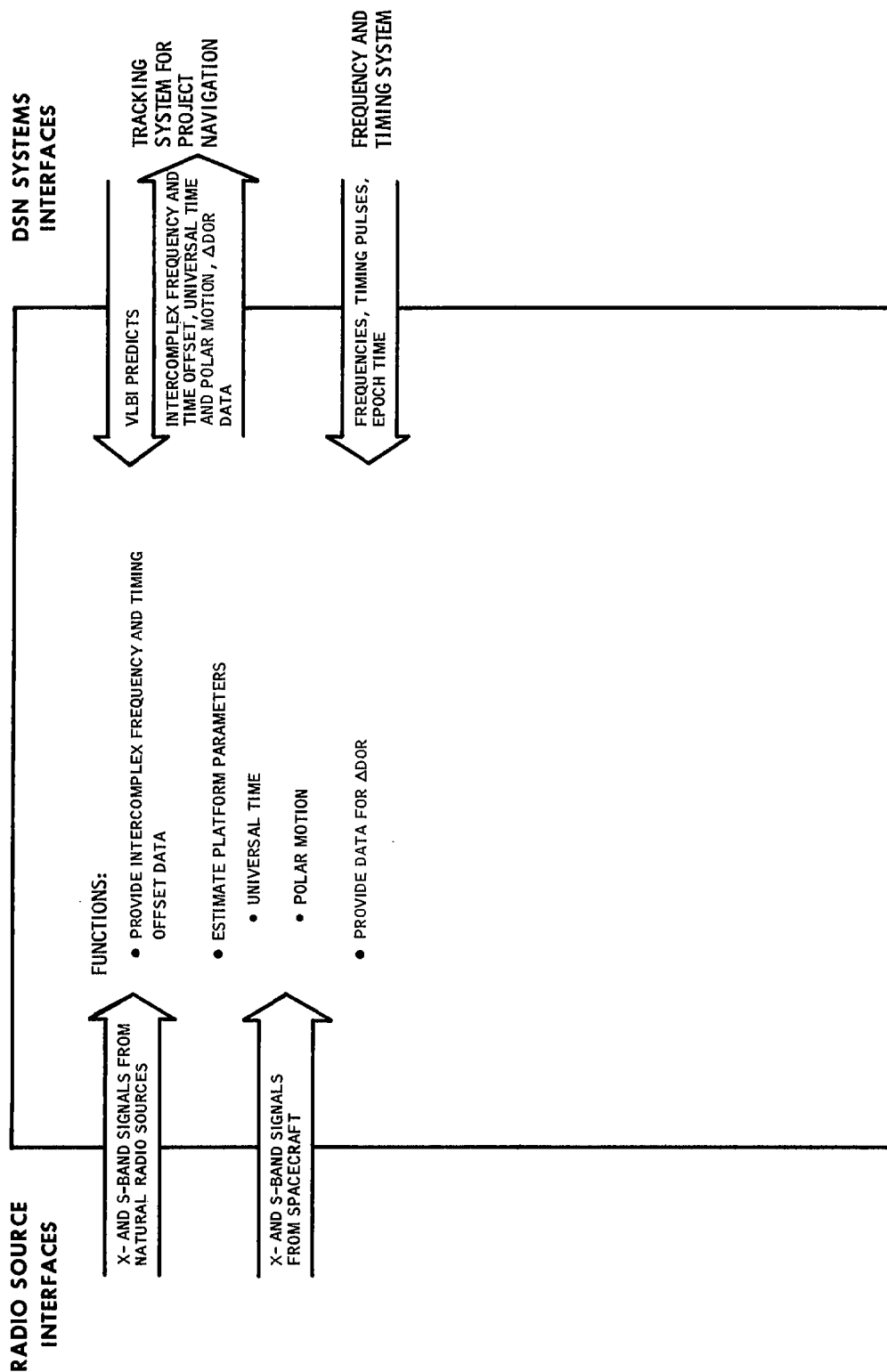


Fig. 2. VLBI System narrow channel bandwidth functions and interfaces

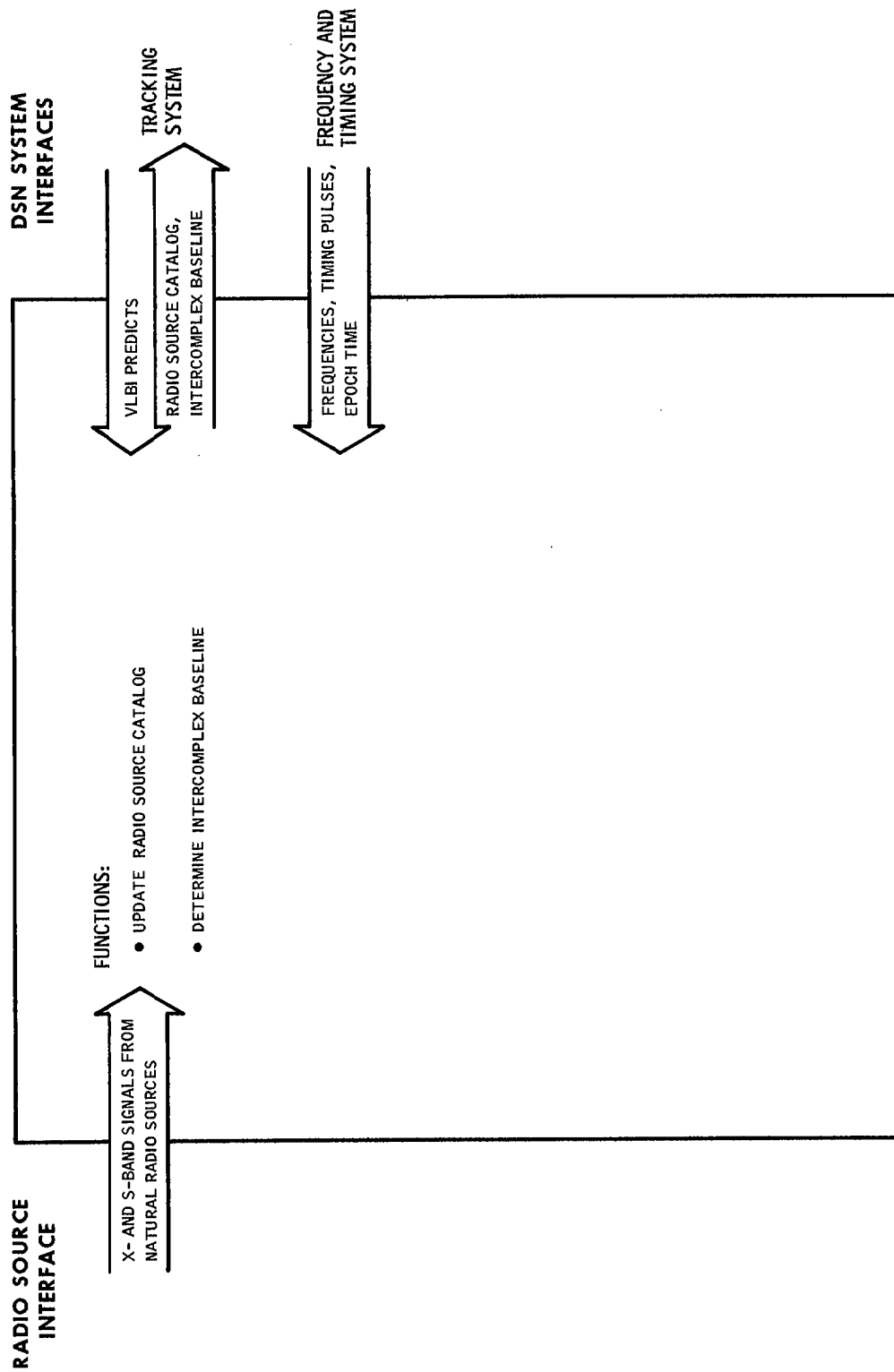


Fig. 3. VLBI System wide channel bandwidth functions and interfaces

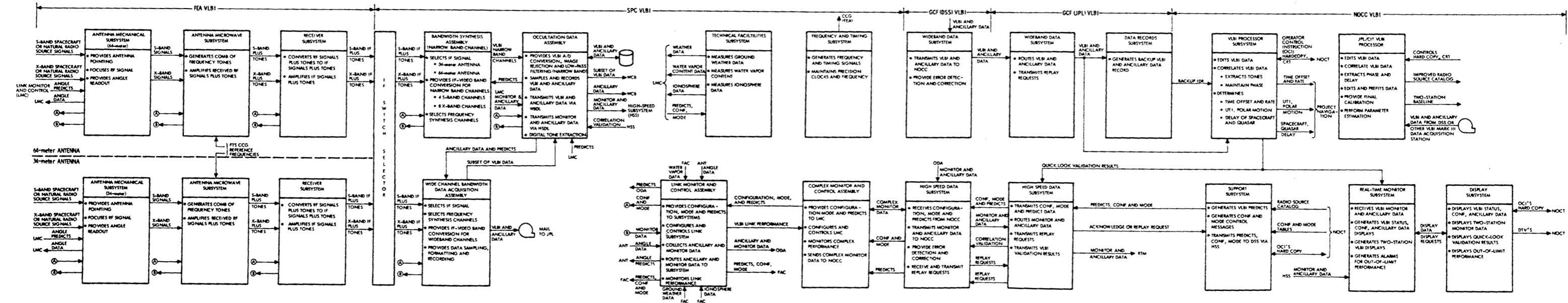


Fig. 4. Functions and data flow DSN VLBI System, Mark IVA-85

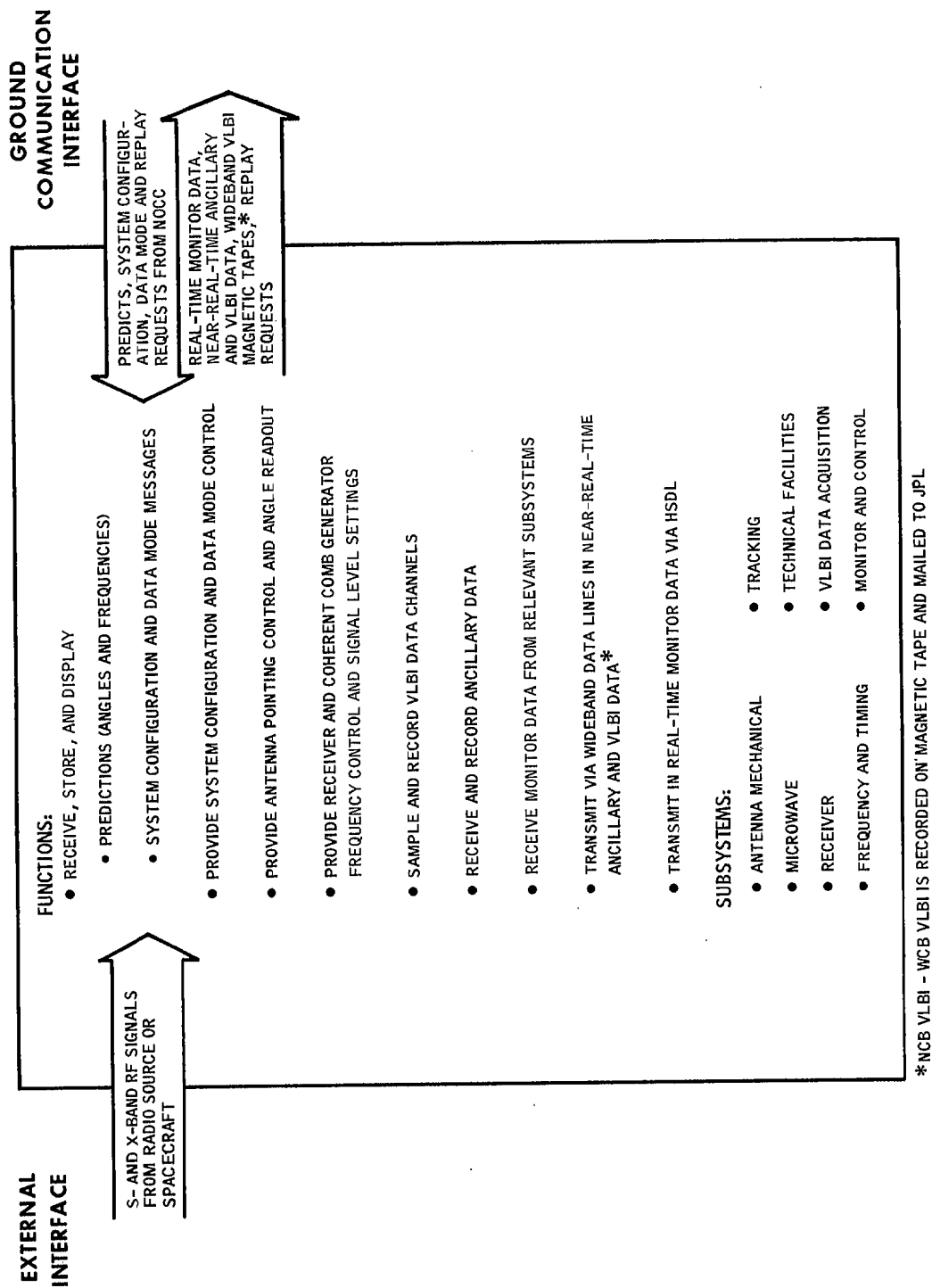


Fig. 5. DSS VLBI System functions, subsystems and interfaces

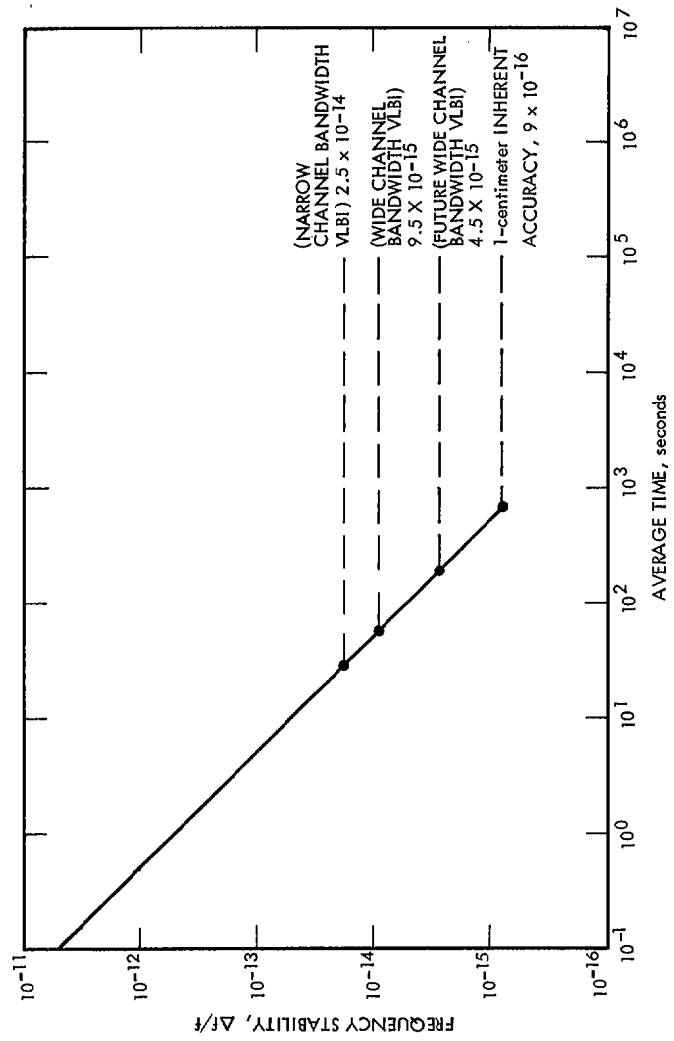


Fig. 6. VLBI frequency stability requirements

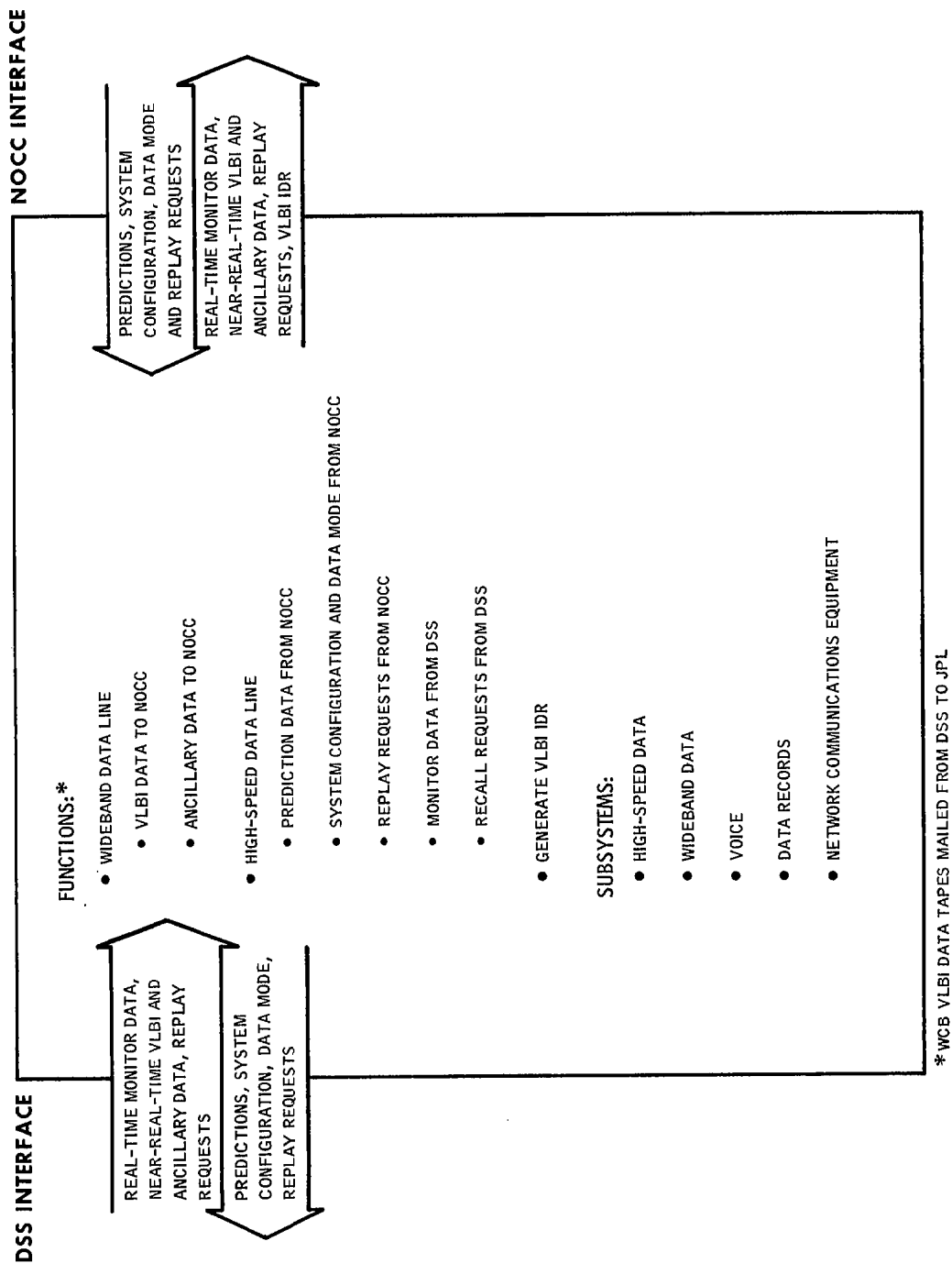


Fig. 7. GCF VLBI System functions, subsystem and interfaces

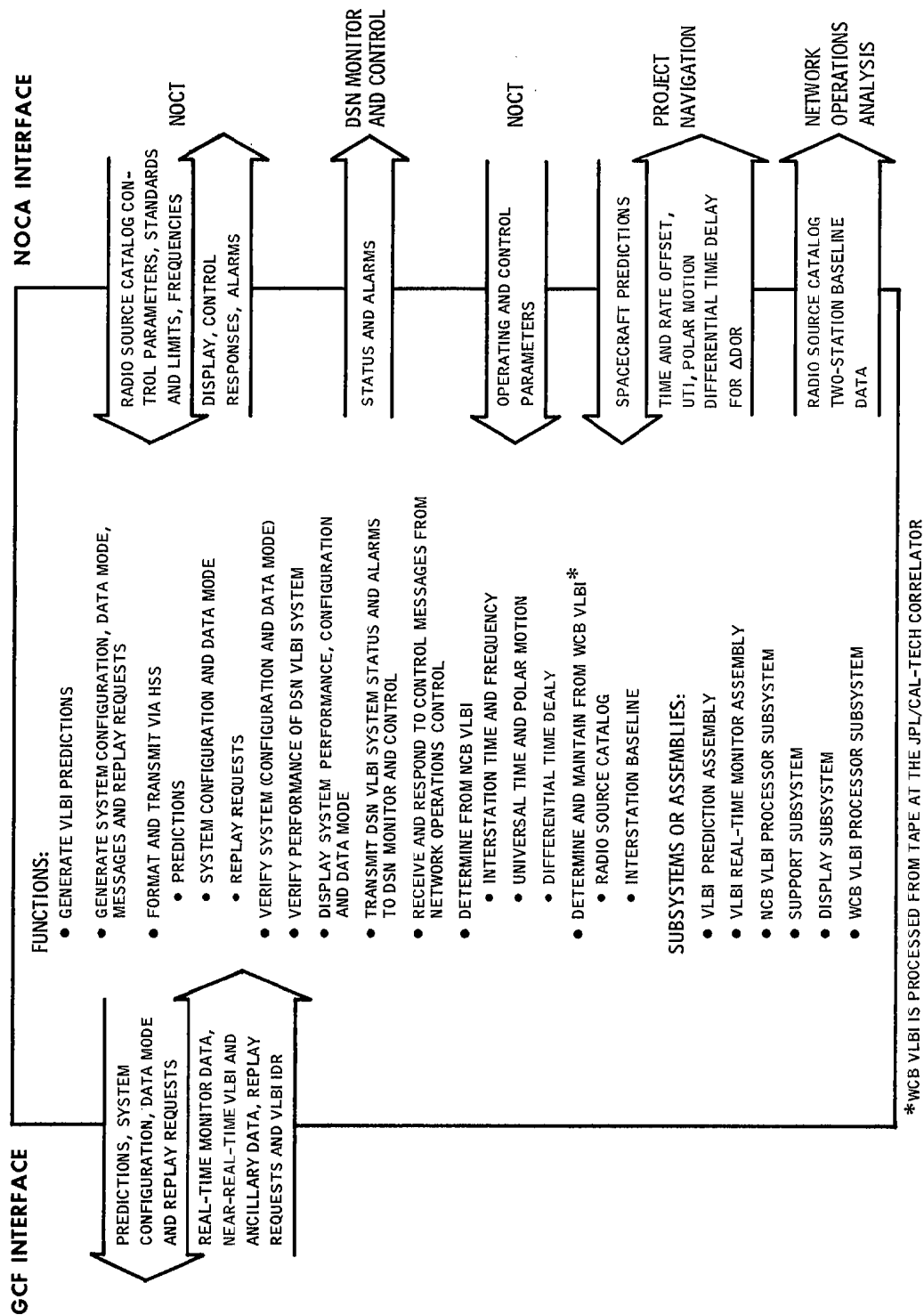


Fig. 8. NOCC VLBI System functions, subsystems and interfaces